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The difficulties resulting from the practical behavior of a windwheel and from the demands made on the electrical generator require the closest cooperation between aerodynamic and electrical engineers. In some general preliminary remarks, we will first discuss these difficulties and their causes as a basis for the necessary understanding between the representatives of the two disciplines, without which successful collaboration cannot be assured. /471*

Then we will report on the experience of the Arbetsgemeinschaft Windkraft (AGW) in their testing of and consultation on projects and experiments concerning electrical wind power plants and on the information obtained through independent scientific work of its specialist on the electrical portion of such wind power plants.

I. General Preliminary Remarks

1. Revolutions Behavior

The operating conditions of electrical power supply require that the voltage be as constant as possible at the point of power consumption. For alternating-current networks, they also require a constant frequency, which demands a constant rate of revolution in the power plant generators. For power plants with steam, combustion, or water-powered generators, adhering to this condition does not present any difficulties, since the energy flux of the power source can be controlled to adapt to the current demand in the consumer network.

* Numbers in the margin indicate pagination in the foreign text.

In contrast, the exploitation of wind power for electrical power generation presents quite different conditions, since there is no way to influence the wind, which varies greatly in direction and intensity, and to regulate it in accordance with the demand of the consumer network.

The variability of wind direction requires that the entire driving apparatus be adjusted to the wind direction at the moment, and is thus a purely mechanical problem. It does not present any particular difficulties from the electrical point of view, and only requires that, in the installation of the generator in the gondola, the connections lead down over slip rings (where the slip-ring apparatus must be designed so that the brushes will not jam if the gondola is stationary for a long period).

On the other hand, one of the main difficulties in electrical wind power plants is due to the extraordinarily large variability of the wind velocity, from motionless air ($v = 0$ m/sec) and light breezes ($v \leq 3$ m/sec) through the range of usable velocities (in the most favorable case, about 3 to 12 or 15 m/sec) up to storms and hurricanes ($v \geq 17$ m/sec).

As the intensity increases, the wind tries to turn the windwheel, and thus the generator it drives, faster and faster. However, this operating property of a windwheel is in complete opposition to the operating conditions for electrical generators described above. Hence, the principal problem which must be solved in electrical wind power plants is to somehow reconcile this conflict in revolutions behavior between fan wheel and generator. In other words, this is a control problem.

2. Characteristic Curves of the Power (C_l) and Torque (C_d) Coefficients of a Fan Wheel; Velocity Ration u/v

In the customary representation in aerodynamics, it is not the actual values for the power and torque of a windwheel which are plotted, but the abstract numerical values of the coefficients C_l and C_d (dimension = [1][1]), and they are plotted as functions of the likewise abstract numerical values of the velocity ratio u/v, where u = the velocity of the tip of the vane. This procedure, which is also used in many other situations, has the advantage that one curve suffices for all wheels of the same construction, regardless of size. By substituting the dimensions, the actual values for power and torque can be obtained as functions of wind velocity and rate revolution, which is proportional to u. However, we must determine whether this representation is suitable for recognizing the problems appearing in electrical wind power plants, and for solving them.

As an example of this customary representation, the characteristic curves of the power coefficient C_l and the torque coefficient C_d are reproduced in Fig. 1.[2]

The same curves are found, with reference to the same source, in the work of Ulrich Noetzlin: "Practical fluid dynamics foundations of wind-powered generators," printed in the Memoir No. 2 of the Reichsarbeitsgemeinshaft Windkraft, March 1941.

The maximum of the characteristic curve for C_l represents optimum exploitation of the energy supplied by the wind. The maximum of the C_d curve represents the maximum obtainable torque. It lies to the left of the point of optimum exploitation, and is considered the pullout point. The left branch of the C_d curve dropping from this point to the stop point ($n = 0$, i.e. $u/v = 0$) is considered unstable, and therefore is out of the question for operation. However, this view also requires a critical

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1 The expression "dimensionless" with the symbol [-] is incorrect and misleading.

2 The broken curves for the low-speed wheel have no relevance for the present report. Refer to [1].

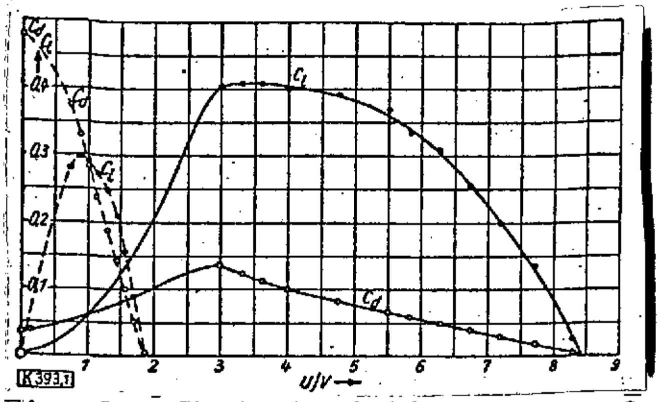

Fig. 1. Characteristic curves of two windwheels.

--- Multivaned low-speed wheel;
—— Three-vaned high-speed wheel;
C_l = Power coefficient characteristic curve
C_d = Torque coefficient characteristic curve
u/v = Velocity ratio

reexamination in the case of electrical wind power plants. It will be seen that it does not hold in every case, and can thus lead to false conclusions.

Fallacies can also arise through the desire (which initially appears quite reasonable) of the aerodynamic engineer for optimum exploitation of the wind energy, based on the power relationship, i.e. the C_l curve. However, this cannot be justified physically, since power is not a primary given quantity, but rather a quantity derived as the product of torque and angular velocity, i.e. of torque and rate of revolution.

3. The Equilibrium Condition for Operation /472

Equilibrium is determined by the equality of torques, i.e. that delivered by the fan wheel to the shaft and that of the generator, which depends on the load, and which counteracts the first torque. The equilibrium state is therefore the intersection of the torque curve of the generator with that of the fan wheel, both as functions of revolutions. In the customary representation of the C_d curve, this cannot be determined without further information, since the C_d coefficient is depicted as a function of two variables, namely u (i.e. rate of revolution) and v, and in fact of their ratio. However, there is no direct physical relationship between the flow velocity of the wind itself and the generator. This relationship is only created through the interpolation of the windwheel, and is entirely incorporated in torque as a function of rate of revolution. Ignoring this fact has lead to false conclusions, as has become evident in further research.

In this connection, we also mention that the author of this report, in subsequent investigations (see Section V) which have not yet been published, initially attempted to conform to the usual representation in aerodynamics with the C_l and C_d coefficients, in order to facilitate the necessary mutual understanding between aerodynamic and electrical engineers. However, this turned out to be completely impossible, because of the physical-mathematical reason mentioned above.

4. The Condition for Stability of the Equilibrium

Establishing the equilibrium state as the intersection of the two characteristic curves does not, however, completely clarify the problem, since an equilibrium can be inherently stable or unstable. Which of the two possibilities holds in the given case depends on the nature of the load torque curve in comparison with the fan wheel drive torque curve as functions of revolutions. Namely, stable operation is possible when the derivative of the load torque curve is larger than that of the drive torque curve -- in other words, when the load curve (i.e. the characteristic curve of the generator) rises more steeply than the drive curve (i.e. the characteristic curve of the wheel) at the intersection of the two curves. Otherwise, the equilibrium is unstable. An example of the latter case is using the windwheel to drive a water pump, which was almost the only type of load for which windwheels were earlier considered. With such pumps, if the lift height is given, the torque increases very slowly as rate of revolution (i.e the discharge) grows. This is because the stall height depends on the quantity of water lifted, and thus on the revolutions of the pump. Hence, in this case, stable equilibrium is only possible on the right branch of the characteristic curve of the wheel from the maximum to the x-intercept of the relieved wheel. With such a load, it is therefore quite justified to call the maximum the pullout point, and to characterize the left branch of the curve dropping off to the stop point as unstable.

With electrical wind power plants, it is therefore necessary to investigate the load-torque curve for a given design of the electrical installation, to determine whether the condition for stable equilibrium is satisfied for the left branch of the characteristic curve of the wheel as well, as indicated by the relative steepness of the two curves.

5. The Linear-Quadratic-Cubic Relationship of Revolutions, Torque and Power as Functions of Wind Velocity

In aerodynamic works, one finds again and again the relationship: revolutions are proportional to the first power of the wind velocity v, torque is proportional to its square, and power is proportional to its cube (we will call this the "linear-quadratic-cubic relationship" for short). This is used as a basis for investigations and analyses, as if it were a fixed law. But this is not at all the case. It is just this cooperation between aerodynamic and electrical engineers, as cultivated in the Arbeitsgemeinschaft Windkraft, which has shown that the evaluation of this linear-quadratic-cubic relationship as a law can likewise result in false conclusions, and consequently in faulty measures.

Namely, the operating situation in the delivery of electrical power also yields very specific operating conditions for the windwheel, which must now be kept in mind by the aerodynamics people and must necessarily be allowed for in designing and constructing the wheel and its mechanical accessories.

Quite apart from the limitation on available power set by the maximum permissible load on the generator (see No. 6), this includes first of all the fundamental recognition that the cubic law, which clearly does hold for the energy of motion contained in the wind itself as a function of wind velocity, does not hold for the power which is exploitable using the windwheel and which can be transformed in the electrical generator.

If the aerodynamic engineers assume that the cubic power curve also applies in general to the windwheel, they overlook that its validity would be based on a very specific postulate: namely, that the velocity ratio u/v is constant for all wind velocities, i.e. that as wind velocity v increases, u, and thus wheel revolutions, grows linearly along with it. Only under this assumption would the windwheel run with optimal exploitation of the wind energy at all wind velocities v, i.e. at one and the same point on the characteristic curve of the power coefficient.

However, as explained in No. 1, such a large change in the rate of revolution is completely incompatible with electrical operations, especially in alternating-current operations connected to the main power system. Consequently, as wind velocity increases, the condition described above as a prerequisite for the validity of the cubic power law, namely constant velocity ratio, is not satisfied at all.

As a consequence, the windwheel, even when designed for the optimum point on the C_1 curve at a specific power and wind velocity, cannot continue to operate at the same point on the characteristic curve as the wind velocity v increases. Instead, as the wind velocity v increases, the ratio u/v will continue to drop. This will shift the operating point on the C_1 curve to the left into the branch dropping off on the left, which is supposedly unstable, and thus correspondingly reduce the amount of wind energy available. Hence, the pure cubic power law no longer applies.

6. Power Limit

In aerodynamic writings, e.g. in the work of Ulrich Noetzlin (op. cit., p. 5), there is a table for the so-called effective windwheel power for various wheel diameters as a function of the wind velocity v, where the term "effective" indicates that the calculation includes the losses up to the coupling with the generator. The power values are computed on the basis of the previously mentioned cubic relationship, in particular with the assumption of "optimum wind exploitation" at a power coefficient $C_1 = 0.385$, and thus in accordance with the formula:

$$N_e = 0.000236 \cdot (\pi/4) D^2 \cdot v^3 \quad [kW]$$

The value of powers found in this way was restricted by Noetzlin himself when he wrote:

"It is obvious that the entire range of wind velocities found /473 in nature cannot be exploited with just one windwheel. The main reason for this is that it is impossible to build a windwheel of relatively large dimensions which is on one hand light enough to exploit low wind velocities with high efficiency, and on the other is sufficiently strong to resist the thrust of the wind at maximum wind velocity and full load."

We should remark that even including in the table values calculated in accordance with the cubic relationship for wind velocities up to 20 m/sec no longer appears justified, since this is a storm. In fact, this point was explicitly noted by Noetzlin in his reproduction of the table.

However, quite apart from these restrictions from the aerodyamic-mechanical point of view, there is also another power limitation on the electrical side. It involves the continuous power of the generator determined by the permissible temperature rise. Therefore, special control measures must be taken so that this power limit for the generator (except for transitory overloads which are tolerable from the point of view of heating) is not exceeded. This control is the main problem in the design of electrical wind power plants.

However, if such limits are set on the power delivered by a wind power plant, there is no sense in tabulating computed "effective windwheel powers" which can in fact never be achieved. There is still another objection to the tabulated values. Since they are calculated with the constant power coefficient $C_1 = 0.385$, they would thus be valid only if the windwheel of given diameter operated with the same velocity ratio u/v at all wind velocities, and in fact with the optimum exploitation of wind energy on which the calculation of the tabulated values is based, as already mentioned. For a given windwheel, however, a constant velocity ratio would mean that the rate of revolution would have to be proportional to the wind velocity. However, as shown in No. 5, this is incompatible with the operating conditions for the generator in electrical wind power plants, for which reason the cubic law for power also fails to holds.

Thus, in order to prevent misinterpretations of the tabulated values, they must not be termed simply "effective windwheel power," but rather "effective power with essentially constant velocity ratio for optimum exploitation of wind power capacity."

7. Power for the Loads in Times of Windlessness and Weak Winds

For those times when it is impossible to use the wind to drive the generator, it becomes necessary to find an alternative for supplying power to the loads, even if only in limited measure. This leads to the problem of storing the energy in times when there is a surplus in energy from the wind with respect to the demands of the consumer network. A second alternative is drawing replacement power from another energy source, e.g. in parallel operation with an existing network. Therefore, these questions must be examined in each individual case in the planning of wind power plants for direct current and alternating current.

II. Direct-Current Wind Power Plants

Such wind power plants are independent, without assistance of an external energy source. No fundamentally new difficulties and control problems arise. Namely, the problem is the same as in electrical illumination for trains. In the latter case, the generator driven by the axle of the car runs with a highly variable velocity, but must still supply as constant a voltage as possible to the lights. Furthermore, arrangements must be made so that the lighting is maintained when the train is stopped or traveling at low speed. These problems have been solved through various systems, so that it would be superfluous to examine them in detail here. We should only mention briefly that the generators can be, for example, armature-reaction excited machines, machines with differential compound windings, Charlet machines, machines with auxiliary exciting windings, auxiliary exciters, etc.

A battery is provided in parallel with the generator, as a buffer for surplus power during times of high wind velocity and as an energy storage unit when there is little or no wind. Since the battery needs a higher voltage to charge than in the discharging state, this condition fits very well the tendency of the windwheel to turn faster within certain limits as wind speed increases. Hence, there are no particular technical problems to be solved in this case either.

With respect to the practicality of such wind power plants, this involves only an economic question: the capacity of the battery, which determines the extent to which the periods of little or no wind can be bridged, influences the capital costs, and thus the price of a kWh. In the present situation, there are also difficulties in obtaining the raw materials, and manufacturing the batteries. Hence, only in urgent, exceptional cases will such DC wind power plants be provided with limited-capacity batteries for economically feasible storage of energy, and only in those cases when, for instance, an isolated farm or forestry station cannot be hooked up to a regional power network. In those cases, the working schedule for motor-driven machines (for example, threshing, chaff cutting, etc.) must be accommodated to wind conditions.

Among the constructed experimental plants which have been examined by the AGW in the course of its consulting activity, there are reports in its publications on the following facilities:

Königs Windstrom-Automat

(first protoype from Ringer, Lichterfelde; further ones from Hein, Lehmann & Co., Berlin-Tempelhof)

Between the windwheel and the generator is a set of gears [2] so that a rapidly turning DC dynamo can be used as the generator. Since the extraordinarily powerfully constructed centrifugal governor keeps the rate of revolution of the wheel in the ratio 100:150 [3] for all wind velocities coming into consideration by adjusting the vanes, and moreover correspondingly regulates the exciting current of the dynamo, it is thus possible to maintain the voltage at a constant level within ±2% in spite of the changes in the rate of revolution. This has been confirmed by measurements at the 5-kW experimental plant constructed in Potsdam-Bornim. According to the designer König, the mechanical arrangement has even made it possible to start the wheel at v = 2 m/sec with the dynamic delivering the full network voltage. At v = 3 m/sec, a power of several hundred watts was achieved, so that is was not necessary to cut in the battery in this range of slight breezes.

Unfortunately, the intensive experiments planned by RAW [Efficiency Committee of the German State Railroad Improvement Works] for this facility [4, 5] could not be completed under the war situation. The facility was temporarily shut down.

Experimental Wind Power Plant Teubert-Gute-Hoffnungs-Huette

The experimental plant designed for 10 kW at v = 6 m/sec was inspected by RAW in November 1941, and is described in detail in Memoir No. 5 of October 1942, p. 59 ff. The generator is a shunt machine with interpoles (catalog model for 111/115 V) driven at high revolutions by the windwheel through interpolationof a two-stage toothed-wheel and V-belt gearing (op. cit., p. 63). The field control is set once by hand and then remains there. Through an automatic switch controlled by a contact-making voltmeter, the generator feeds a battery of 54 cells with an auxiliary tap for 48 cells. The energy for the loads is drawn from the battery. Whenever the generator voltage is large enough so that the battery can be charged, the entire battery is connected to the generator by the automatic switch (charging position), and the load voltage drawn from the auxiliary tap. If the generator voltage is too small, the machine is completely disconnected by the automatic switch, and the load voltage drawn /474
from the entire battery (discharge position).

This circuit has proved capable in practice of compensating for voltage fluctuations of the generator adequately for the loads.

Combination Mechanical-Electrical Plant in a Mill

The facility was designed by mill owner R. Triller on his own initiative. Due to the wartime difficulties in obtaining materials, it was largely constructed of used parts ([6], see also [7]). The power is transmitted from the three-vaned windwheel through a bevel gearing with a 1:5 gear ratio to a vertical shaft, and from this with a 1:1 gear ratio to the mill transmission shaft at 225 rpm. This horizontal shaft drives in reverse extension a DC machine, which operates in combination with an accumulator battery.

Both the DC machine, which is used as generator and motor, and the mill transmission can be shut off during operation through a slipping clutch. The rate of revolution of the windwheel is held at 45 rpm with the halves of the battery in series.

The electrical portion consists of a slow-running shunt machines (from Schwartzkopf) with a 23 kW rated power at 220 V. By connecting the exciter winding in parallel, the rate of revolution is reduced, in accordance with the rated voltage of the battery of 110 V, to 210 rpm in generator operations and to 170 rpm in motor operation -- also reducing the rated power to 11 kW. The machine employed is significantly over-designed; however, due to the provisioning difficulties at the time, a low-speed machine of appropriate power could not be found. In new planning, the dynamic will be designed in conformity with the attached mechanical devices.

The battery consists of 54 cells with a capacity of 360 Ah, and thus can supply 30 to 35 kWh of energy, depending on the discharge time. The rated voltage depends on the charging state, and varies between 110 and 150 V. A series-parallel circuit is provided for the battery. By throwing a switch, the two halves of the battery can be connected in parallel or in series. In the parallel circuit, the rated voltage of 55 V is characteristically reached at a low wind velocity (at about 2.5 m/sec). In this way, irrespective of the mechanical-electrical interconnections, wind intensities of 4 to 5 m/sec, which are not otherwise exploited in mill operation, can be used with high efficiency for charging the battery.

As soon as the wind has risen to 2 to 3 m/sec after a lull, the charging of the battery begins in the parallel circuit. The mill machines are still disconnected, i.e. just to overcome the idling losses in the generator. Hence, the slight wind is well exploited. If the mean wind velocity increases to 5 m/sec in the meantime, the halves of the battery are switched to series, and the mill machines are connected in. Depending on the charging state of the battery, either the entire mill or just a part of it can operate with constant revolutions, since the missing power is drawn from the battery by the machine operating as a motor. If there is surplus power, it is pumped into the battery. In this way, the wind is completely exploited up to the set wind velocity at which the control mechanism of the vanes responds. If the wind drops, the machines do not have to be disconnected for the time being. Only when the wind remains low for a relatively long time is it necessary to switch to the most appropriate combination of mill machines, in order to keep from draining the battery completely. In the mechanical-electrical compound operation, however, the load on the battery is quite small, since it is only called upon for a fraction of the related power. Its life can therefore be assumed to be at least 10 years.

The basic advantage of such a mechanical-electrical coupling is that continuous operation is possible even with fluctuating winds, and that in particular, small wind velocities of 2 to 5 m/sec are completely exploited.

According to observations made in the operation of the plant, the wind has a mean velocity bewteen 4 to 5 m/sec, and fluctuates between about 3 and 6 m/sec. With such variations, the rate of revolution of the compound device fluctuates by ±2 to 3%. In addition, the variations in revolutions can be influenced by appropriate design of the electrical machine in accordance with the conditions to be satisfied. Thus the rate of revolution can be kept constant enough to satisfy the requirements of modern mill machinery for uniform driving.

In addition to the fluctuations induced by the wind, there are also variations corresponding to the charging state of the battery. However, these variations do not cause any trouble, since the operating point moves continuously and slowly. When the battery is charged, the friction losses are merely larger due to the higher rate of revolution.

AGW has inspected the plant. Measurements convincingly demonstrated that it was working well.

III. Wind Power Plants for Alternating-Current Operation

In the general preliminary remarks, we referred in No. 1 to the difficulties which the revolution behavior of the vane wheel and of the electrical generator creates in exploiting wind energy using wind power plants and in its conversion to electrical power. The operating property of the windwheel -- that is the wind tries to turn it faster as the wind intensity increases -- is in conflict with the operating conditions for the generator. In alternating-current synchronous operation, these conditions demand not only that the rate of revolution be as constant as possible in order to maintain the voltage, but that it actually be precisely constant, in order to maintain the frequency. It is now very interesting to observe how the problem of overcoming this conflict in revolution behavior has led, in the researches of RAW and AGW, to new information and proposals, which yield substantial simplifications in the facility in comparison with the measures first coming into consideration.

One of the projects presented to RAW for inspection and consultation was a large wind power plant (10,000 kW, 12,000 kVA, cos ϕ = 0.8) from Kleinhenz in combination with the Maschinenfabrik Augsberg-Nürnberg (MAN) and the firm Boveri & Co. (BBC), Mannheim. In this project, the variability in the rate of revolution, and thus also in the frequency, of the alternating-current generator driven by the windwheel was viewed as an unalterable fact. To overcome the conflict with the network conditions, the first solution was to place a transformer arrangement with grid-controlled inverters between the generator with variable frequency and voltage, and the network. This transformer setup had the job of transforming both the voltage and the frequency, which fluctuated due to the variations in rate of revolution, to the values prescribed for the network. This assumed that the electrical facility was to operate in parallel on the load end to an existing network fed by synchronous machines, which dictated the constant frequency and voltage. Of course, this interpolation was a technically feasible solution. However, the transformer setup with its transformers, inverters, and switching and control devices both increased the expense and reduced the efficiency, quite apart from the heightened complexity and the resulting greater maintenance for the entire installation.

It was now due to Dr. Kade, director of the firm BBC, in a second design for the same wind power plant, that the incompatibility of the operating properties of the windwheel with the operating conditions of a synchronous generator was recognized for what is was: namely, an illusion.

At the instigation of RAW, the author of the present report, as a member of RAW and as its specialist for the electrical segment of the wind power plant, studied more closely the problem of directly driving synchronous generators, and presented his results in a detailed work ([8]. (Refer to Design I and II of Kleinhenz-MAN-BBC. See also [9]). To determine the feasibility of directly driving synchronous generators, the resulting load situations were illustrated on the basis of a curve diagram (see [9], Fig. 2), which had already appeared with appropriate explanations in the second Technical Report of RAW of September 1941, and which is here reproduced as Fig. 2. It depicts two torque characteristic curves of a fan wheel, as given in aerodynamic works for the so-called characteristic torque coefficient curve C_d as a function of the velocity ratio u/v, i.e. as a normalized numerical value. Our representation holds for the case of constant wind velocity. The lower curve applies to the wind velocity $v = v_n$ associated with the rated operating point B, the upper curve for a wind velocity 10% higher, $v = 1.10\ v_n$. We can also obtain the advantage of the usual representation in normalized numbers (getting along with just one curve for windwheels of different size but the same construction) if the abscissa is not the actual rate of revolution, but its ratio n/n_n to the rated operating rate of revolution n_n (here, the synchronous rate of revolution of the generator), and similarly, /475 the ordinate is not the torque M_d but rather its ratio M_d/M_{dn} to the rated torque M_{dn}. The curve is identical with the C_d coefficient curve, the only difference being the change of scale for the abscissa and ordinate. As discussion, we take from the previously mentioned work the following selected explanations with simultaneous reference to the general preliminary remarks made in the first section of the present report.

When the wheel is relieved, the rate of revolution rises, and would assume the intercept rate at point A if the wheel were completely relieved. In practical situations, the value at this

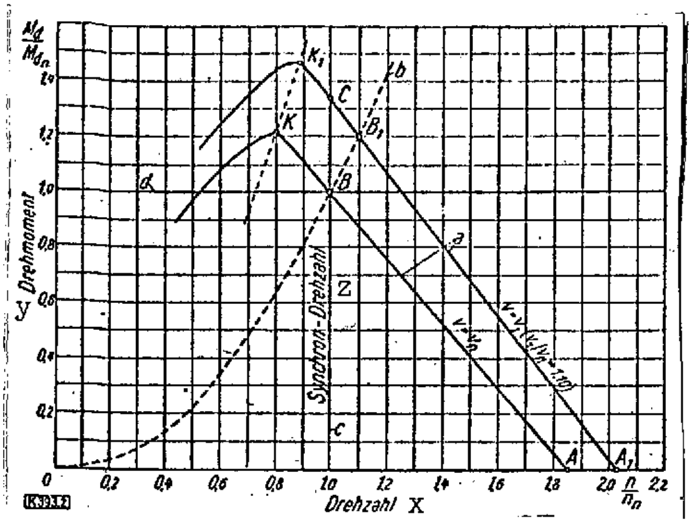

Fig. 2. Operating characteristic curves determining the stable load states.

a. Two torque/revolutions characteristic curves of the fan wheel for constant wind velocities written above the curves in each case

b. Parabola for constant velocity ratio u/v.

c. Characteristic line of the synchronous generator, simultaneously synchronous rate of revolution.

d. Rate torque $M_d = M_{dn}$.

Key: x. Rate of revolution; y. Torque; z. Synchronous rate of revolution

point in the given case is about 1.85 times the rated revolutions. This is of course not a fixed value; rather, it depends on which point of the characteristic curve is selected as the rated power (point B).

As the rate of revolution decreases, the fan wheel torque first continues to increase to its maximum K and then drops off on the left branch of the curve to the stop point (n = 0, i.e. u/v = 0). The position of the rated operating point B is assumed in the region of optimum exploitation of wind power, in accordance with aerodynamic practice (see preliminary remark in No. 2).

Now when the wind velocity v changes, for instance from v_n to 1.10 v_n, we can derive a second curve for this higher wind velocity from the given curve by constructing it pointwise for the identical flow conditions in each case, i.e. for the same velocity ratio u/v. This would then change u and thus also the rate of revolution n in proportion to the wind velocity, so that $M_{d1}/M_{dn} = (v_1/v_n)^2 = (n_1/n_n)^2$. With these assumptions, the operating point B then shifts in accordance with the parabola law to the point B_1 on the new characteristic curve for $v_1 = 1.10\ v_n$. In the same way, the point K moves along a parabola to K_1. The intercept A for $M_d = 0$ moves along the horizontal axis linearly to a value 1.10 times as great, i.e. from 1.85 to 2.035 at point A_1. Thus the new curve is obtained from the old one, displaced from the latter upward and to the right.

It is doubtless correct to apply the parabola law for the purpose of deriving the characteristic torque/revolutions curve for different, but constant wind velocities. This construction is based on the assumption that associated points on the two curves have the same flow conditions for the vanes, i.e. the same velocity ratio u/v. In the operation of a wind power plant, however, the windwheel is not at all bound by such a condition, neither on the part of the wind nor on the part of the load. Instead, events in driving an electrical generator, in our case a synchronous generator, are determined by the equilibrium condition, which, as indicated in No. 3 of the preliminary remarks, is based on the equality of the torques, and is thus given by the intersection of the characteristic torque curve of the fan wheel with that of the generator, both with respect to the rate of revolution at constant wind velocity. However, the synchronous generator is bound by the frequency condition to a constant rate of revolution, and its characteristic curve is therefore a straight line parallel to the vertical axis at the point $n/n_n = 1$ (see Fig. 2). However, this curve does not intersect the second characteristic wheel curve derived for $v/v_n = 1.10$ at the point B_1 found from B by extending the parabola, but at the point C which lies vertically above the point B.

But this provides the proof for the correctness of the discovery made by Kade and incorporated into the second plan of the Kleinhenz-MAN-BBC wind power plant, that the constant rate of revolution demanded of the wind power plant by electrical requirements does not rule out using the windwheel for directly driving the generator. This discovery brought about substantial progress in that the originally envisioned, costly, complicated, efficiency-lowering inverter-transformer installation could be eliminated.

Nevertheless, as became evident in oral discussions at the MAN plant in Gustavsburg, the second design still reflected the influence of the view that the square law held at least for torque as a function of wind velocity. The fact that not only this law, but the linear-quadratic-cubic law in general is not a fixed law in actuality was clearly expressed by the author of the present report in a Technical Report on the Kleinhenz-MAN-BBC project [10]. See also the discussion in Section 1, No. 5 on this point.

As far as the actual quantitative relationships go, the diagram with its curve for the 10% higher wind velocity shows at the equilibrium point C an increase in the load torque by a factor of 1.34, in other words, considerably more than the 1.21 given by the square law. The increase is even a bit more than the third power, which would yield a factor of 1.33. This also implies that the power is not inherently proportional to the third power of wind velocity. The view which treats and evaluates the linear-quadratic-cubic relationship as an established law must therefore be tossed overboard, due to the operating condition of constant rate of revolution forced on the fan wheel by the electrical components.

In addition, we should remark here that the 1.34-fold increase in the torque found above when the wind velocity increases by 10% is not a value which holds in all cases. Instead, it depends on the position of the chosen rated-power point on the characteristic curve. If, for example, the synchronous rate of revolution were chosen so that the rated-load point coincided with the maximum K, the load point would then shift from K, with the relative value 1.21

(see Fig. 2), to the point directly above it on the second curve with the relative value 1.43; this would increase the load on the generator by a factor lf 1.43/1.21 = 1.18, in other words, less in this case than would be given by the square of the ratio of wind velocities.

The relationships derived from out diagram are extraordinarily important, because they lay the foundation for judging how much the generator would be overloaded as wind velocity increases, and which measures should be taken to prevent unacceptable overloads.

However, the fact that the equilibrium of the fan wheel and generator torques is determined by the intersection of the two characteristic curves, demonstrating that it is possible to drive a synchronous generator with a windwheel, does not fully clear up the problem of the equilibrium. It remains to be seen whether the equilibrium is stable or unstable, in line with the statements in No. 4 of the preliminary remarks. The synchronous generator curve is parallel to the vertical axis, so its derivative $dM_d/dn = \infty$. The derivative of the fan-wheel curve is negative on the right branch, and finite and positive on the left branch. Thus, the stability condition (which states that the generator curve must be steeper than the fan-wheel curve at the intersection) is satisfied over the whole range of the characteristic curve from the stop point to the intercept. Hence, for synchronous operation, the left branch cannot be described as unstable, as is the case in driving a water-hauling pump. Similarly, the maximum K loses its significance as a pullout point.

The absolutely necessary collaboration of electrical and aerodynamic engineers thus requires that the principles on which the plans and studies of the latter are based by subjected to critical reexamination. In addition, they should discard once and for all the notion that the linear-quadratic-cubic relationship is a generally valid law.

On the other hand, these discoveries also oblige electrical engineers to avoid uncritically adopting this supposed law into /476
their own studies.

The fact that synchronous operation is also possible on the left branch of the fan wheel curve will prove to be extremely important and valuable in the light of subsequent investigations.

The remarks on the equilibrium state, which is based physically on the torques, inevitably imply the correctness of the statement already made in the preliminary remarks at the conclusion of No. 2 that starting from power, i.e. the C_1 coefficient curve, as a primary given quantity, cannot be justified. Instead, power is derived from the torque and the rate of revolution. In every case, it is the torque relationship which is crucial for the operating state, and hence it is the primary given.

Once again, we will report on further results of studies conducted by the author in his work on using large wind power plants to directly drive synchronous generators [8].

a) Transient Behavior Due to Variations in Wind Velocity and the Influence of the Fan-Wheel Curve on the Damping.

The current load on the synchronous generator depends on the lead angle of the magnet wheel compared to its idling position. If the load is to go from point B to point C as a result of an increase in the wind velocity from v_n to 1.10 v_n, the lead angle must increase correspondingly, and this requires an acceleration of the wheel, and thus a temporary increase in the rate of revolution. However, this triggers a transient which is damped due to the damper winding situated in the pole shoes. The investigation of this transient has now shown that, at operating points on the right branch, such as B and C, the driving torque drops due to the (temporary) increase in velocity. This acts in the same way as a damping coming from the generator itself. Hence, there is intensified, and thus favorable, damping for the transient.

Next, if the rated operating point B is chosen so that the associated point C vertically above it coincides with the maximum K_1 of the second curve, the fan-wheel torque for the oscillation region is independent of the temporary variation in revolutions. There is then no increase in damping due to the fan wheel, and the oscillation behaves like a pure natural oscillation of the generator. But when the new load point C lies to the left of the maximum K_1, the fan-wheel torque increases as the rate of revolution rises (i.e. hypersynchronization). However, in opposition to the previous case, this does not signify a reinforcement, but rather a weakening of the damping, and thus prolongation of the required decay period. Therefore, if the natural damping of the generator is greatly weakened, the oscillation could be reinforced, producing the danger of falling out of synchronization. The quantitative investigation of the numerical example taken from the Kleinhenz-MAN-BBC design has shown, however, that such a weakening of the damping is not to be feared. In this example, it would only be on the order of about 2.4% of the natural damping.

The investigation of the transient is first conducted in the research for the most unfavorable case of a sudden change in wind velocity, which is hardly to be feared in reality. The maximum amplitudes of oscillation and slippages were computed for this case.

Then the investigation was carried out for the case of a steady (i.e., not sudden) increase in wind velocity to the higher value of v_1 = 1..0 v_n within a period of T_W, which was (arbitrarily) set equal to the time constant T of the decay curve. However, as continued studies of the author during the printing of the work demonstrated, the oscillatory decay curve was not correctly depicted, due to an assumption made for the purpose of simplification. In reality, under the assumptions made, the curve does not swing back, and is thus more favorable than the one displayed in the accompanying diagram.[3] Accordingly, in the real case, with a steady growth in wind velocity, the possibility of a large overload on the generator, along with the danger of falling out of synchronization, will be much less than given in the work.

For reliable advance calculation of the load conditions for wind-powered alternating-current generators, it will be necessary to determine the steepness of the fronts of gusts using automatically recording wind meters. The radio-tower experiments planned in this direction by the RAW in its time in consultation with the Reichspost [German Post Office] were unfortunately not carried out due to the difficulties of the war period, and were even less possible under the conditions of the postwar period.

b) Regulation of Power

Another problem treated in the work is the necessity and nature of power regulation. Following the example of the curve reproduced in Fig. 2 for $v_1 = 1.10\ v_n$, different characteristic curves can be drawn for even higher wind velocities. The intersection C of these curves with characteristic synchronous curves will initially move upward on the right branch, increasing the equilibrium torque, and thus also the load on the generator.

However, there is a limit on the power increase as wind velocity grows, as previously indicated in the preliminary remarks in No. 6. This limit is due to the continuous power level set for the generator in accordance with the VDE [Association of German Electical Engineers] regulations with reference to the allowable

[3] The author takes this opportunity to thank Prof. Küpfmüller and Prof. Leonhard for calling his attention to this error in the depiction of the oscillatory decay process after they received preprints from ETZ.

heating, quite apart from the danger of falling out of synchronization at excessively high loads. Hence, it would not do any good to be able to extract more power from the available energy of the wind per se. Instead, as will be explained in the following, it is absolutely necessary to regulate power as a function of wind velocity.

However, this regulation cannot be undertaken at the generator, since any change in the excitation would only give rise to a reactive current, while the generator would have to work with a torque forces on it in a sense by the fan wheel through corresponding power delivery to the parallel governing network. Thus, there is only one solution: regulation of power at the fan wheel end, i.e. mechanically. Therefore, measures must be taken to ensure that the fan wheel does not deliver more than the maximum permissible torque, regardless of wind velocity. The simplest and most proven means for this purpose is shifting the vanes.

This measure must also ensure that the M_d curves shifted upward and to the right for higher wind velocities (such as the example for $v_1 = 1.10\ v_n$ in Fig. 2) are pushed downward far enough by altering the angle of incidence of the vanes, so that the equilibrium point on the synchronous line does not exceed the maximum permissible torque. For successful cooperative planning of electrical wind power plants, the aerodynamic engineer must therefore collect for the electrical engineers characteristic fan-wheel curves for various angles of incidence. This also applies to lower wind intensities, which displace the characteristic curves downward if the vane positions are fixed, thus diminishing the generator power. It is then necessary to know how far the characteristic curves can be lifted by appropriate changes in the angle of incidence, i.e. at which wind intensities the full load of the generator can be otained.

After we had proved that, contrary to the generally prevalent opinion, the left branch of the torque curve was not unstable in synchronous operation, but makes possible and assures thoroughly stable function, we now had to examine the extent to which there was a danger of overload in this region. A favorable circumstance now came to our assistance: Due to the drop on this branch, the elevation of the intersection with the synchronous line caused by raising the entire curve, and thus the danger of overloading the generator, was somewhat reduced. In aerodynamic terms, this means: If u is constant, raising v decreases the velocity ratio u/v, and thus the efficiency of wind exploitation drops on the left branch of the curve. This is in no way a drawback; instead, it has quite a favorable effect, in the sense of diminishing the risk of overload.

From these considerations, a rule could be deduced for a large wind power plant in parallel operation with a governing network, namely, that the generator should run at its rated load as base load on the system in the widest possible range of wind velocities, while all load fluctuations in the network must be assumed by the other generators of the main governing power plant.

A special case of regulation occurs when the main switch of the wind power generator is triggered, i.e. the generator load torque suddenly drops, so that the fan wheel, and with it the pole wheel, tries to assume the rate of revolution at the intercept. In order to keep the rise in revolutions within reasonable limits, the torque of the fan wheel must be reduced by shifting the vanes. Finally, regulation through shifting the vanes is also necessary in starting up the wind power plant and in synchronizing the generator with the network.

As far as the control of the power regulation is concerned, the just-mentioned case of "racing," since the electrical power has disappeared, is a purely mechanical problem. The natural type of control is therefore that of using the increasing rate of revolution by means of a centrifugal governor to operate the vane-shifting mechanism.

In the loaded generator state, the load should be held as constant as possible as the wind velocity varies. However, it would be inappropriate to use, for example, a current relay to influence the vane displacement, since this would also react to an increase in the reactive current (in the event of over-excitation of the generator). The power delivered by the generator would have to be used as a control quantity; the relay would thus have to be constructed on a wattmeter basis. In this case, the response value of the relay would have to be made adjustable. /477

c) Criticism of Other Proposals for Power Regulation

The quantitative calculations carried out on the example of the investigated design have now produced a very important piece of information, which indicates how important it is that the mechanical regulation of power function very rapidly, in order to prevent any unacceptable overload of the generator, with the possible danger of stalling. This process must therefore act in a few seconds, if it is to be effective. This should be achievable with vane shifting without any other measures.

At the same time, this point provides a criterion for evaluating the feasibility of other proposals for power regulation, e.g. by turning laterally out of the wind the swivel head which bears the fan wheel (which must be provided in any to align the wheel in accordance with the wind direction), or, as in a proposal of H. Honnef, by tilting the fan wheel or even a large frame with three wind wheels. However, with the huge masses to be moved in a large wind power plant, such control measures could hardly be completed in a few seconds, but would instead take many minutes, probably half an hour or more. Completely apart from all the mechanical difficulties which face such constructions, and which are beyond the bounds of this discussion of the electrical side of the plants, electrical-engineering considerations with regard to overload and the danger of the generator falling out of synchronization, this type of regulation can be rejected on principle as completely unworkable.

In Memoir 6, March 1943, p. 17 (which appeared later), Kleinhenz made a proposal for an alternative to the large generator installed directly into the fan wheel, as provided in the Kleinhenz-MAN-BBC project. In order to better exploit the energy of the wind, the power of the windwheel would be transmitted through a high-power set of gears with a gear ratio of 10.5 at 500 rpm to four rapidly turning generators, which could be switched on and off as needed as the wind velocity changed.

The same idea can be found in Memoir 8, October 1944, p. 52, in an article by A. Lieske on the "Construction of small and medium-sized wind-power plants for exploiting wind velocities from 6 to 20 m/sec through drawing variable power."

These proposals are well-founded, and appear implementable.

d) Danger of Resonance

The work also indicates a danger of resonance resulting from the number of vanes due to the periodically recurring jolts as the vanes pass in front of the tower, if these jolts have roughly the same frequency as the natural oscillations of the generator.

e) Using Asynchronous Generators in Large Wind Power Plants

And finally, we investigate whether there would be any advantages to using an asynchronous generator, after such machines (at any rate, only with small wind power plants) have been successfully employed (110 kW from Russian Winds [11]). The result is that for reasons of operating reliability, with the large diameters coming into consideration, the air gap would have to be much larger than would normally be indicated by the relatively small pole pitch. This would yield an extreme increase in the magnetizing current (to a multiple of the normal value) to be provided by the network, and thus an unacceptably poor cos ϕ. This would be too high a price to pay for the advantages of using asynchronous generators: elimination of the DC excitation, elimination of a synchronizing device, and absence of the oscillatory tendency. The idea of building asynchronous generators directly into the fan wheel for large wind power plants must therefore be discarded.

IV. The Present Task: Providing Small Wind Power Plants for Supplying Agricultural Regions

Under present conditions, the construction of large wind power plants will be out of the question for a long time. All projects in this direction will therefore have to be rejected at the outset as utopian.

In continuing the work of the former RAW, AGW has therefore faced reality, and, with the approval of the responsible authorities, has directed its efforts toward the recognized and acknowledged immediate task of facilitating the provision of agricultural regions with electrical power, and has presented this in a Memoir [12] to the responsible authorities for information, approval, and support of the plan.

In accordance with the standards set by the RAW, the wind power plant should be designed so that, allowing for the gearing efficiency, it provides a power of 25 kW at a wind velocity of 7 m/sec. The continuous power of the generator with the heating limit set by VDE rules should be about 33.5 kW. In that case, with the machine dimensions under consideration, the "rated operating power" of the wind power plant, at 25 kW (see above), will still be in the range of the best efficiency.

In Appendix II of the Memoir, on p. 6, the use of asynchronous generators for the electrical part of the facility is recommended and justified as follows:

"In its design with the cage rotor, the asynchronous machine is the simplest, most easily manufactured, and most reliable machine. It functions in hypersynchronous operation as a generator. In comparison with the synchronous machine, it has the advantage that it exhibits no vibrational tendency with load jolts, and requires neither direct-current excitation nor synchronizing devices, since it is not rigidly bound to the network frequency, but only 'elastically' in line with the power-dependent hypersynchronized slippage. The drawback in comparison with the synchronous machine is that it draws its magnetizing current from the feeder network, so that the latter, just as the power plant generators, would be afflicted with considerable reactive currents at the cost of the effective transmissable power. However, this drawback can be eliminated by compensation of the asynchronous machine by means of capacitors in parallel."

The use of asynchronous machines recommended here may seem at first glance to contradict the rejection of this type of machine in the previously cited work of the author. However, there is no fundamental contradiction. Namely, the rejection referred merely and explicitly to large wind power plants, and was based on the unusually large air gap required for these machines for operating reliability reasons, with its detrimental and unacceptable consequences with regard to drawing of reactive current. However, such considerations do no apply to the small wind power plants under discussion here, since in this case rapidly running normal machines can be used with the interpolation of a gear.

However, today there are still other difficulties (aside from the obstacles in obtaining materials and manufacturing due to the zone boundaries) in the operation of the planned small wind power plants. These are due to the extraordinarily strong reduction produced by war and postwar measures in the power capacity of the still-available power plants, and to the irregular acquisition of outside power. The inevitable consequence of this situation is that, in the event the plants are overloaded, or particularly in the event of a breakdown of machines or boilers, the voltage and especially the frequency cannot be held constant with the reliablity customary under normal conditions. Experience has shown that it must be anticipated that the frequency in the MEW [Märkische Electrizitätswerke AG] system may drop under certain circumstances as low as 40 Hz, for both short and long periods. This complicates the regulation problem. Namely, the latter is not restricted to the power regulation discussed in the report on large power plants. There is also the regulation of the /478
hookup of the generator to the governing network as the wind comes up and the windwheel starts. To avoid dangerous overload jolts, the hookup must take place at a very specific frequency. For synchronous generators, as mentioned, it would be tied rigidly to the network frequency, and, moreover, the phases of the voltages would have to match, while with asynchronous generators, this link is termed "elastic" in view of the slippage. However, since the load on the generator depends on the hypersynchronous

slip, it must be hooked up only within the permissible slipping range. For greatest convenience, it would be carried out as near as possible to synchronization. If the network frequency is reliably constant, it could be triggered in a purely mechanical way, using a centrifugal governor adjusted to the desired hypersynchronous rate of revolution.

However, when, as anticipated, unexpected frequency fluctuations must be anticipated, such a purely mechanical hookup control, responding only to a specific rate of revolution, is not sufficient. The relay switches must instead by controlled as a function of frequency, i.e. influenced from the electrical side of the network, and in fact in line with the frequency existing at just that moment in the feeder network.

The electrical-engineering committee appointed by AGW for dealing with the electrical portion of the wind power plants has studied this problem intensively in collaboration with experts of the Berlin firms SSW and AEG as well as with representatives of MEW and BEWAG. It arrived at a proposal worked out in detail by SSW-Neugebauer, according to which the frequency dependence would be secured by an asynchronous motor in the feeder network, the so-called frequency motor, whose subsynchronous rate of revolution can be tuned to a specific ratio to the desired hypersynchronous rate of revolution of the generator. The switch mechanism is designed so that the following features can be achieved with it:

1. by means of a cup anemometer: establishing and indicating the wind velocity (roughly v = 3 m/sec) at which the windwheel should be set in motion, through hooking up the frequency motor;

2. hooking up the generator to the network;

3. the actual regulation process through modifying the vane positions as a function of the varying wind velocity for the purpose of holding the continuous power of the generator constant over the widest possible range of velocities;

4. disconnecting the generator and stopping the entire facility when the highest permissible wind velocity is reached (about $v = 20$ m/sec);

5. by the same token, stopping the entire facility when the network voltage falls to zero. If, within a short time, the voltage is restored, and there is sufficient wind, and the frequency motor is then turned on by the anemometer, it immediately restarts, and the facility automatically returns to operations;

6. when the protective switch, which is in front of the whole facility, is triggered by overload or short circuit, the facility shuts down until the switch is manually rethrown.

Details on the envisioned switch setup must be reserved for a later report.

The well-prepared design of the entire electrical system meets the requirement of the AGW for a completely automatic facility. Such operation is necessary, since in rural districts, the costs of maintaining a technically trained, permanent work force to operate and service the wind power plant would be unacceptable.

As far as the mode of operation of these small wind power plants is concerned, it differs in a fundamental respect from that considered for large wind power plants and described in the discussion of the Kleinhenz design. In the latter case, the plants involved were to furnish considerable power to the governing network, and were to be as constant a base load as possible for supporting and relieving the main power plant. In the case of the planned small wind power plants, on the other hand, the generator power is normally fed to the local consumer network, and the magnetizing reactive current drawn from the governing network (in the event that and to the extent that it cannot be compensated for by using capacitors in parallel, as indicated).

The need for consumer power, however, fluctuates, and cannot always be met with the power available at the moment from the wind. The parallel operation with the governing regional network provides the opportunity to first cover a deficit in wind power directly from the feeder network and, secondly, and importantly, to deliver a surplus of wind power back to the feeder network. This return to the governing network thus takes the place of the buffering and storage obtainable in DC plants by batteries in parallel.

It should also be mentioned that the price-rate difficulties which can easily appear with such drawing and retuning of electrical power are to be eliminated by the intended absorption by MEW of all planned wind power plants into the firm itself.

Another equally well-prepared proposal for frequency-dependent control of the hookup of the generator and for regulation of power using modification of vane positions has been presented to AGW by Rostocker Industriewerke (RIW). They have begun work on one of the planned 25-kW wind power plants as an experimental plant; this is to provide, through systematic testing in operation. the required information for facilitating the most effective standardization of the remaining plants for mass construction. The 50 small wind power plants mentioned in the Memoir are to be just the beginning of a much more extensive plan, so that the manufacturing price for the individual plant, and thus also its influence on the price of the generated kWh, can be greatly reduced by mass production.

In addition, the manufacture of such plants in great numbers after the testing of the first plants would also be of great importance for the export which we so urgently require.

In accordance with the proposal of the RIW, the relay switch is to be controlled as a function of frequency by using a centrifugal governor, which is driven by an asynchronous motor in the feeder network, corresponding to the frequency motor in the SSW proposal. Power is to be controlled as a function of wind velocity by adjusting the position of the vanes through a mechanical system operated, reasonably enough, by the wind itself.

Initially, it was intended that the experimental plants should be designed with the control proposed by RIW. However, as a precaution, the switching and control system proposed by SSW-Neugebauer should also be installable, in order to test this one in practice as well. An agreement has been reached in conferences among the design specialists of the two firms by which the electrical facility shall at first be constructed in line with the SSW proposal.

There is one thing further to report as far as completed experiments with small wind power plants in parallel operation with a governing alternating-current network. An alternating-current motor has been experimentally installed as an hypersynchronized asynchronous generator in the compound mechanical-electrical plant built by mill owner R. Triller and described in Section II (Direct-Current Operation). The result was that the system could function with complete success.

V. Further Development Work

As already mentioned, automatic operation is vital for the planned small wind power plants for supplying electrical power to agricultural districts. However, this places great demands on the /479 control mechanism from both the mechanical and the electrical points of view. The principal problem in the sence of maximum operating reliability is a mechanical one: creating an automatic, absolutely reliable control of the vane-shifting mechanism, in order to effectively protect the generator from unacceptable overloads, and in fact by keeping generator power constant as wind velocity grows from 8 or 8.5 m/sec, at which point is should have reached its full load dictated by the heating limit, up to storm conditions, at which point the vanes must turn into the feathered position.

On the other side is the consideration of costs in manufacture and operation, which yields the requirement of maximum simplification of the entire facility.

These considerations have now induced the author to investigate, in continuation of his prior work [8], whether the problem of power regulation can somehow be simplified even further, without being compelled to sacrifice anything with respect to operating reliability.

These investigations have now produced new information, the result of which may at first appear quite paradoxical:

Namely, under certain conditions, it is possible to achive by simple means self-protection of the generator from overload in parallel operation with a governing alternating-current network, making any mechanical regulation of power using modification of vane positions superfluous over a rather wide range of wind velocities.

The resulting advantages in simplification of construction, manufacture, and expenditure with a simultaneous increase in operational reliability is so obvious that no detailed description is necessary.

The means for achieving such self-protection is simply the appropriate choice of the rated operating point for the wind power plant on the torque-revolutions characteristic curve of the fan wheel.

And the necessary condition is:

first: that the operating point on the torque curve of the fan wheel corresponding to the generator power limit lies to the left of the maximum on the decreasing, supposedly unstable, but in reality (as has been shown)) thoroughly stable branch, and

second: that this part of the decreasing left branch fits as closely as possible a specific, mathematically representable form.

The investigations were conducted for synchronous and asynchronous generators.

The detailed proof for this discovery will appear in an exhaustive work. It is not yet in a form ready for publication, but, as soon as it is completed, it will be published by the AGW in a Memoir, like the previous work of the author.

Discussion of further details would far exceed the space allotted for the present report, and must therefore be reserved for a later report.

It should be mentioned at this point, that to implement this discovery achieved by the author through theoretical studies, it is absolutely necessary to obtain from the aerodynamic people the following information:

1. the production of torque curves (or C_1 coefficient characteristic curves) from measurements in model tests. If such curves are not available, it would be urgently necessary that the appropriate experiments be performed in the wind tunnel.

2. on the theoretical side, it would be necessary to calculate the left branch from the flow conditions, and especially to determine whether it is possible to influence the form of the left branch, through suitable design of the vane profile, or other constructive measures, in such a fashion that the given condition is satisfied as well as possible on an extended segment.

VI. Summary

The difficulties resulting from the operating behavior of a windwheel and the demands on the electrical generator -- namely, approximately constant voltage, and, with alternating current in parallel operation with a governing network, precise adherence to the frequency of this network -- require the closest cooperation between aerodynamic and electrical engineers.

The customary representation in aerodynamics of the power and revolutions coefficient curves as functions of the velocity ratio u/v of the windwheel is unsuitable for investigating the equilibrium conditions for the operation of the electrical wind power plant. These conditions are not determined from the power curve, but from the torque curves of the windwheel and generator, not as a function of u/v, but just as a function of the rate of revolution, where the equilibrium is given by the intersection of the two characteristic curves. The stability of the equilibrium is determined by the relative steepness of the generator curve in relation to that of the windwheel curve. For an electrical wind power plant, the branch dropping off to the left of the maximum to the stop point can therefore also be stable. In operation with synchronous generators, this condition is always satisfied.

By virtue of the operating conditions forces on the windwheel by the generator, the well-known aerodynamic linear-quadratic-cubic relationship of rate of revolution, torque, and power as functions of wind vleocity loses its significance as a law of general validity.

Aside from the power limit dictated by strength of the windwheel itself, there is also another limit due to the generator based on the continuous power limit set by VDE rules in consideration of the permissible heating.

The most appropriate form for this regulation is the proven method of modifying the position of the vanes. Other proposed methods, such as turning the wheel out of the wind or tilting the entire drive mechanism, must be rejected because of the inevitable resulting dangerous overloading of the generator.

In spite of the difficulties mentioned at the outset due to the operating behavior of the windwheel and the operating conditions for the generator, directly driving a synchronous generator in parallel operation with a governing network is quite feasible, so that the interpolation of a transformer arrangement with grid-controlled inverters originally thought necessary for large wind power plants can be eliminated.

Based on a prior work of the author, further statements were made regarding the oscillatory decay process taking place in synchronous generators in the event of sudden increases in wind velocity, and the resulting influence of the fan-wheel curve in the right and left branches on the damping.

The generator power can be better matched to the available wind energy by (in accordance with proposals of Kleinhenz and Lieske) interpolating a high-power set of gears and furnishing several rapidly running generators, which can be switched in or out as needed.

Reference is made to the danger of resonance, which can result from the number of vanes.

The use of asynchronous generators with installation in the fan wheel must be rejected for large power plants, since mechanical operating security would demand an extremely large air gap, and this would require an unacceptably large magnetizing current.

Since, under the present conditions, the construction of large wind power plants will be out of the question for a long period, the AGW, in keeping with the needs of the present, is working on the plan for setting up small wind power plants for servicing agricultural areas in the district of the Brandenburg-Mecklenburger-Electrizitätswerke (BMEW) in parallel with its network, and in fact by using asynchronous generators. A prerequisite is completely automatic operation with frequency-dependent control of the hookup of the generator.

The report also contains some figures on the experimental plants for alternating and direct current which have been worked on by AGW.

In the final section, a result is reported from a further, as yet unpublished, investigation of the author. This indicates that it is possible to achieve, under certain conditions, self-protection from overload for a wind-powered alternating-current generator in parallel with a governing network, making any control involving vane position superfluous over a rather wide range of wind velocities.

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